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Results from LIGO Searches for Binary Inspiral Gravitational Waves

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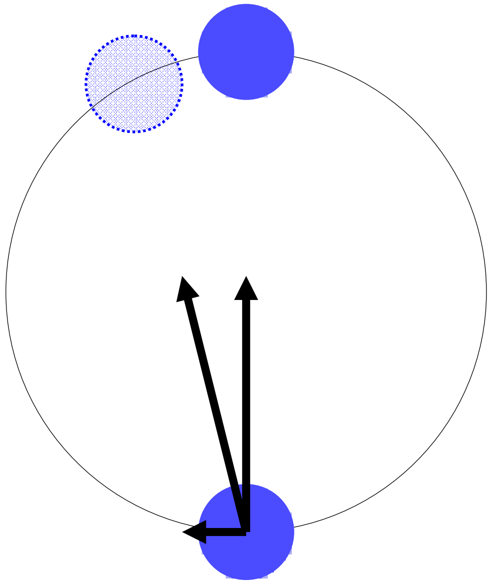
Intro to Relativistic Orbital Dynamics



Consider a binary system in a close orbit

Each object is accelerated tangentially due to the retarded gravitational potential

Evolution of orbital radius and frequency:

$$\frac{dr}{dt} \propto \frac{-GM}{c} r^{-1}$$

$$\frac{df}{dt} \propto \frac{(GM)^{1/3}}{c} f^{7/3}$$

Objects spiral in until they finally coalesce

Energy and angular momentum are carried away by gravitational waves

Additional relativistic effects kick in as orbit shrinks

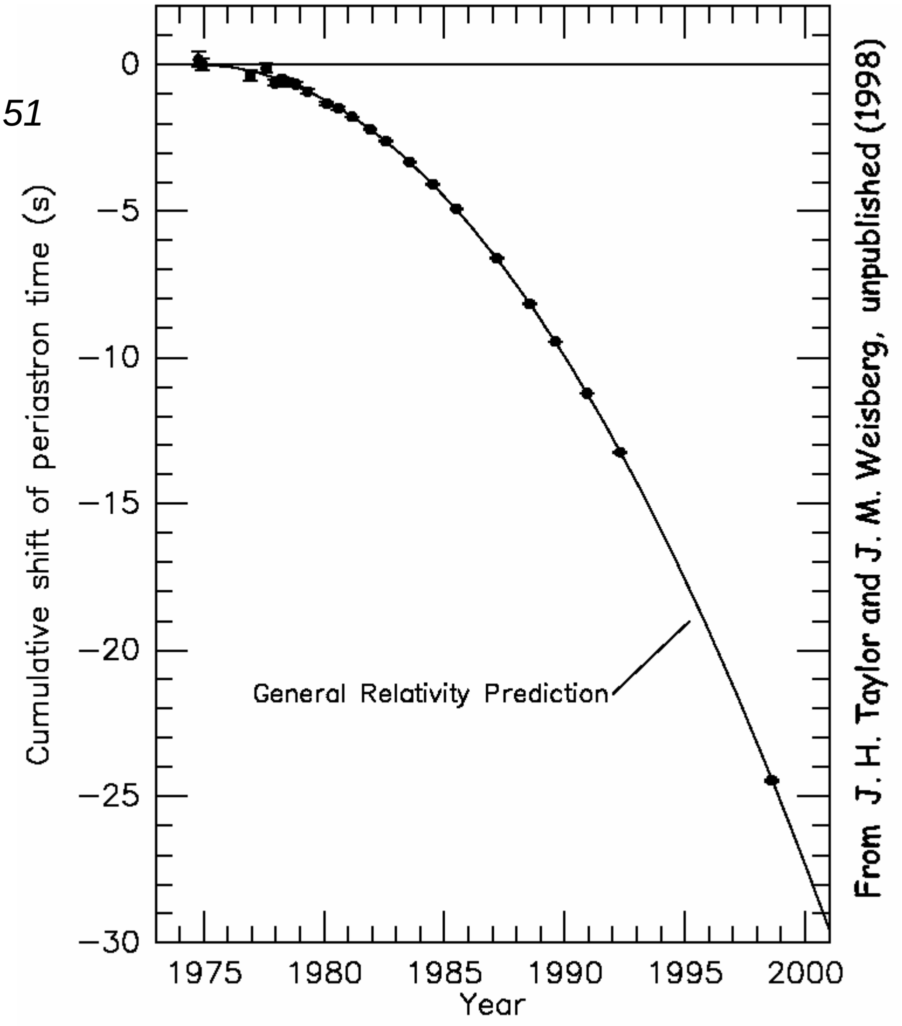
Famous Binary Neutron Star Systems

PSR 1913+16

Hulse and Taylor, 1974 *ApJ **195**, L51*

Masses: 1.44 $M_\odot$, 1.39 $M_\odot$

Orbital decay exactly matches prediction from gravitational wave emission



From J. H. Taylor and J. M. Weisberg, unpublished (1998)

PSR J0737-3039

Burgay *et al.*, 2003 *Nature **426**, 531*

Orbital period = 2.4 hours

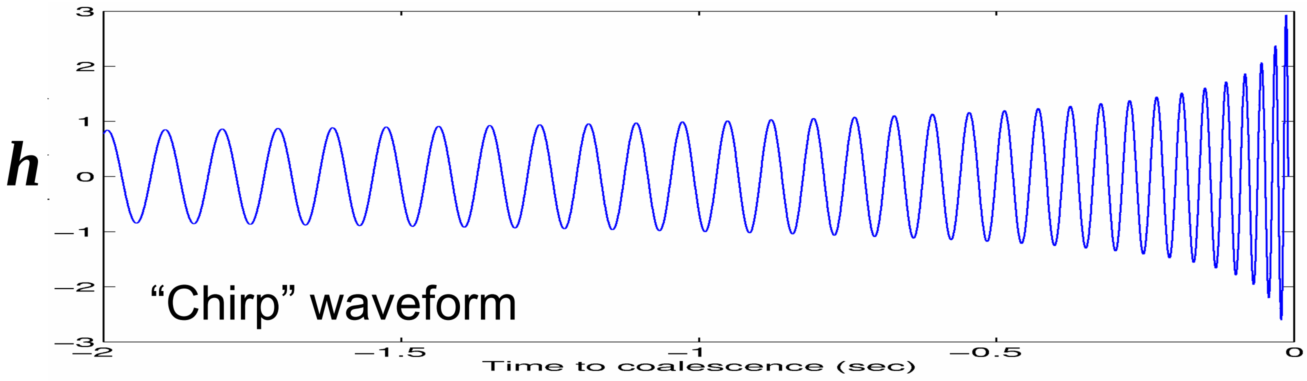
Will coalesce in ~85 Myr

Will yield improved tests of G.R.

Inspiral Gravitational Waves

For compact objects (neutron stars & black holes), inspiral accelerates up to the point of merger

Gravitational waves emitted at twice orbital frequency



“Chirp” waveform

In LIGO frequency band (40–2000 Hz) for a short time just before merging: anywhere from a few minutes to <<1 second, depending on mass

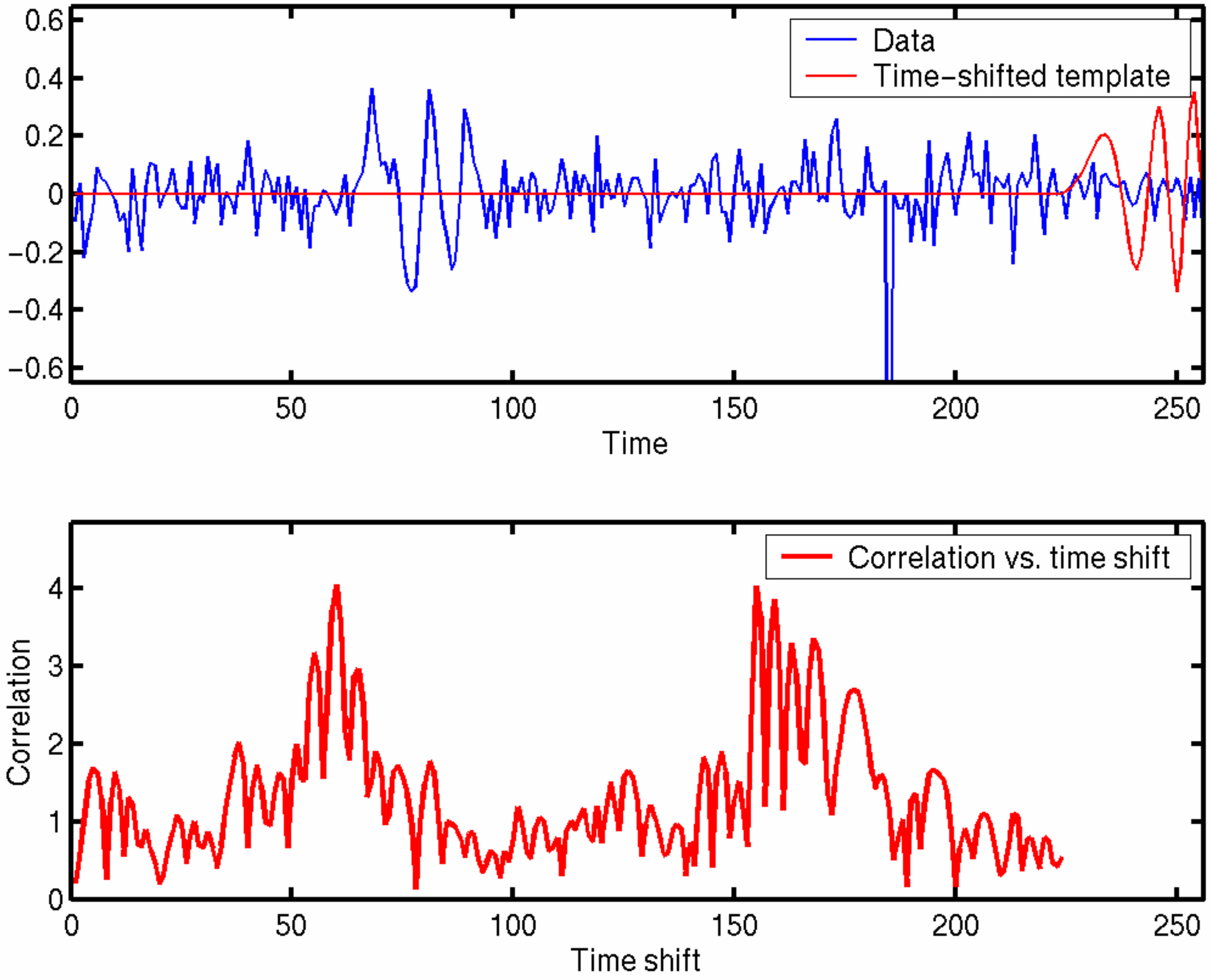
Waveform is known accurately for objects up to ~3 $M_\odot$

“Post-Newtonian expansion” is adequate ➔ Use matched filtering

Higher-mass systems are more complicated

Non-linear G.R. effects and spin can have a significant effect on waveform

Illustration of Matched Filtering



Binary Neutron Star Inspiral Rate Estimates

Can base estimates on the observed systems, or on population synthesis Monte Carlo

Kalogera *et al.*, 2004 *ApJ* ***601****, L179*

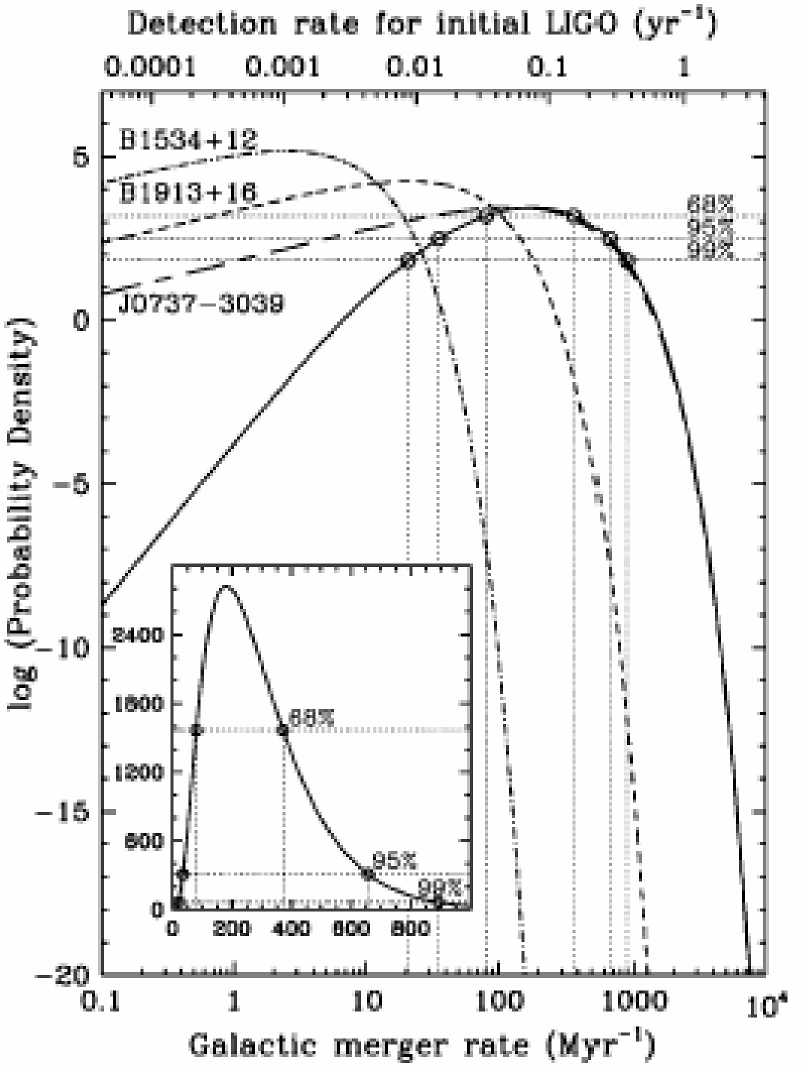
- Statistical analysis of the 3 known systems with “short” merger times
- Simulate population of these 3 types
- Account for survey selection effects

For reference population model:

(Bayesian 95% confidence)

- Milky Way rate: 180^{+477}_{-144} per Myr
- LIGO design: 0.015–0.275 per year
- Advanced LIGO: 80–1500 per year

Binary black holes, BH-NS: ???



LSC Inspiral Analysis Working Group

Active members:

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Overview of Inspiral Search Technique (1)

Use optimal matched filtering in frequency domain

Template Data

$$z(t) = 4 \int_0^\infty \frac{\tilde{h}(f)\ \tilde{s}^*(f)}{S_n(f)}\ e^{2\pi i f t}\, df$$

Noise power spectral density

Look for maximum of $|z(t)|$ above some threshold ➔ "trigger"

Describe with template params, SNR ρ, effective distance D

Check consistency of signal with expected waveform

Divide template into p frequency bands which contribute equally, on average

Calculate $$\chi^2(t) = p \sum_{l=1}^{p} \left\| z_l(t) - z(t)/p \right\|^2$$

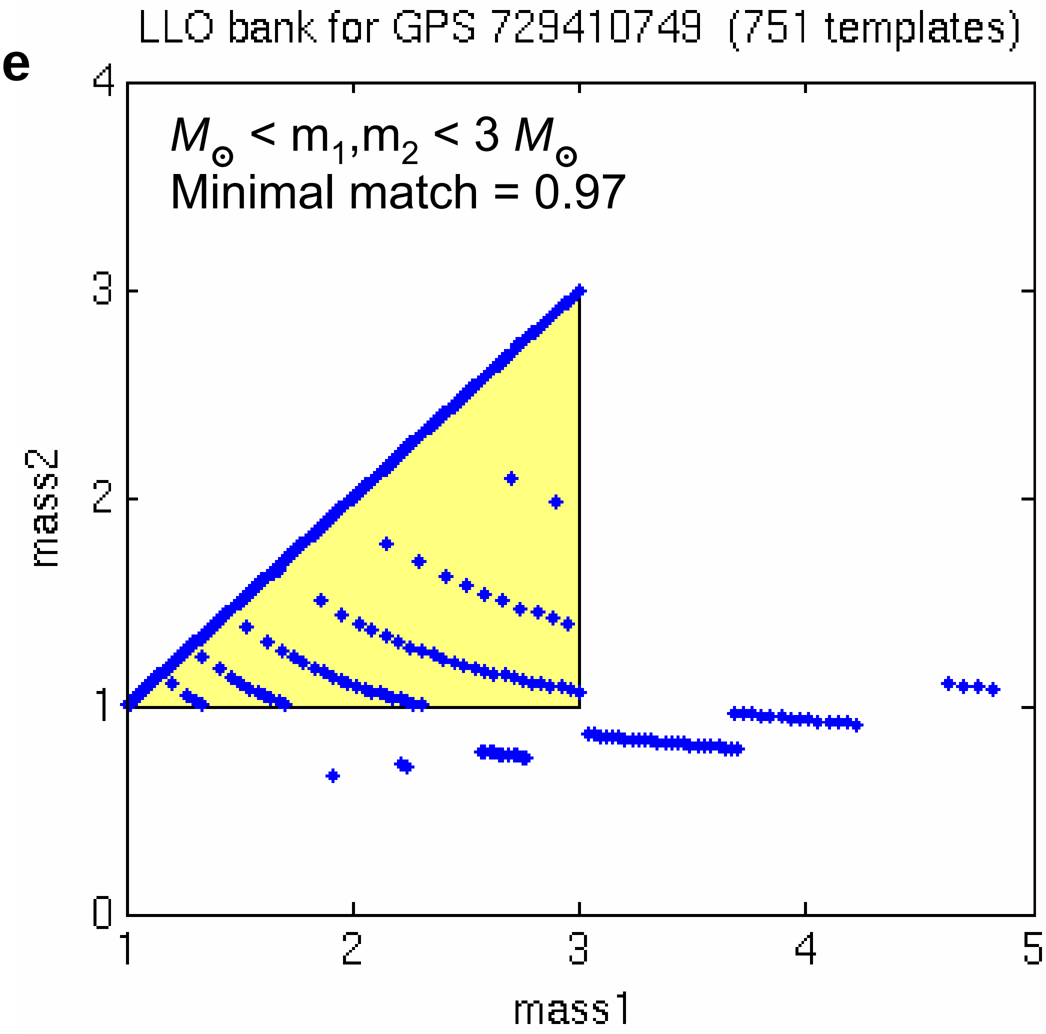
Other waveform consistency tests are being considered

Overview of Inspiral Search Technique (2)

Use a bank of templates to cover parameter space

Require a certain "minimal match" with all possible signals

Process data in parallel on many CPUs

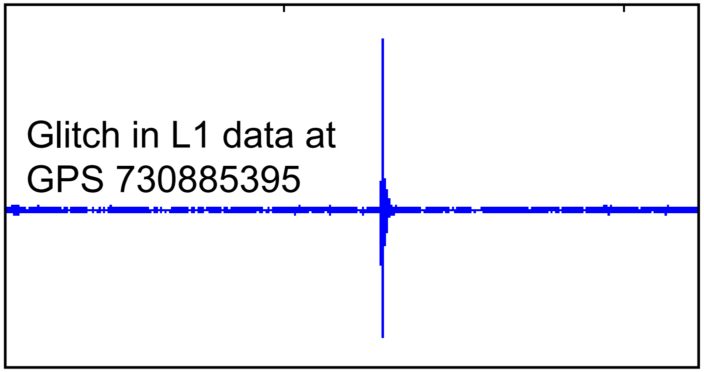


Overview of Inspiral Search Technique (3)

Process only good data, based on data quality checks

Validate search algorithm with simulated signals

Use auxiliary channels to veto environmental / instrumental glitches



Tune algorithm parameters and vetoes using "playground" data

- ~10% of data, excluded from final result

Require coincidence to make a detection

- Consistent time, signal parameters in multiple interferometers
- Eventually, will do coherent analysis

… or set an *upper limit* on event rate, using a population Monte Carlo to determine the efficiency of the analysis pipeline

Previous Binary Neutron Star Inspiral Search Using S1 Data

Binaries with component masses between 1 and 3 $M_\odot$

2nd-order post-Newtonian waveforms are reliable; spin effects negligible

Visible range for 1.4+1.4 $M_\odot$ (optimally oriented, with SNR=8)**:**

L1 ~175 kpc ← Milky Way and Magellanic Clouds
H1 ~38 kpc
H2 ~35 kpc

Analyzed 236 hours of data when L1 and/or H1 was running

Used “maximum-SNR” statistical method to set an upper limit

Efficiency of search calculated by Monte Carlo

Simple spatial model; mass distribution from population synthesis model

Result (90% C.L.): Rate < 170 per year per MWEG

[Milky Way Equivalent Galaxy]

To appear in Phys. Rev. D; gr-qc/0308069

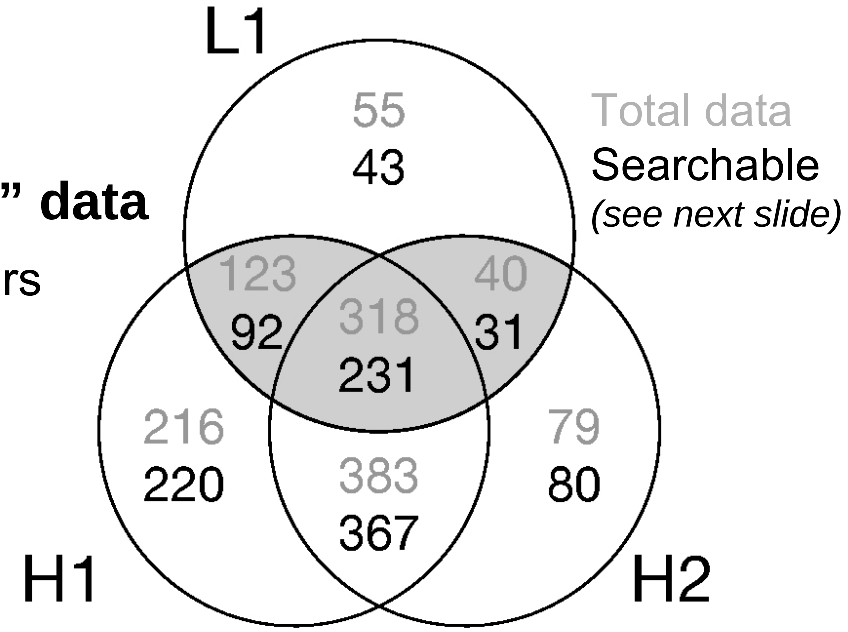
S2 Data for Inspiral Searches

Visible range for 1.4+1.4 $M_\odot$ (optimally oriented, with SNR=8)**:**

L1 ~1.8 Mpc
H1 ~0.9 Mpc
H2 ~0.6 Mpc

Over 1200 hours of “science mode” data

Various combinations of interferometers



For this analysis, use only *coincident* data from both sites

“L1 and (H1 or H2)”

Avoid “H1 and H2 and not(L1)” due to concerns about correlated glitches from environmental disturbances

➔ Use data from which a believable detection could be made

481 hours total, 355 hours searchable

Data Selection and Processing

“Data quality” cuts – omit times with:

- Data files missing, or outside official S2 run epoch
- Calibration information missing or unreliable
- Servo control settings not at nominal values
- Timing problems in hardware
- High broadband noise in H1 interferometer for at least 3 minutes
- Photodiode saturation

These things reduce amount of data searched for inspirals

Data processed in “chunks” 2048 seconds long

- Ignore good-data segments shorter than 2048 seconds
- Filter code does not search for triggers in first or last 64 sec of each chunk
  ➔ overlap chunks to analyze entire good-data segment except ends
- Noise power spectrum estimated from data in each chunk;
  interferometer response calibration averaged over chunk

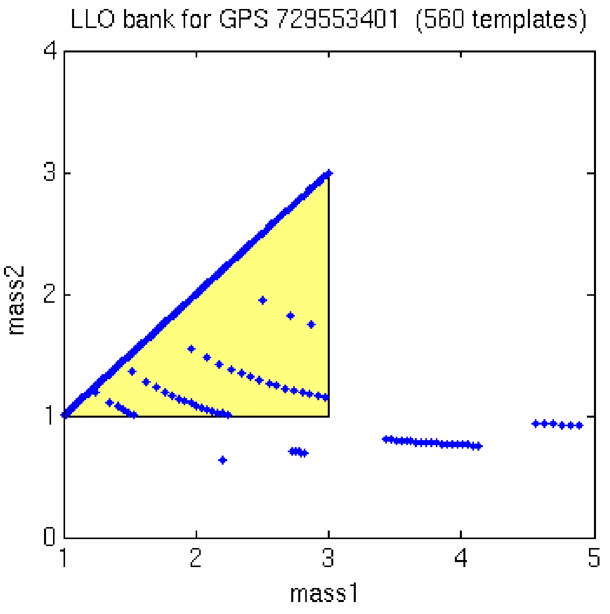
“Playground” data processed together with other data

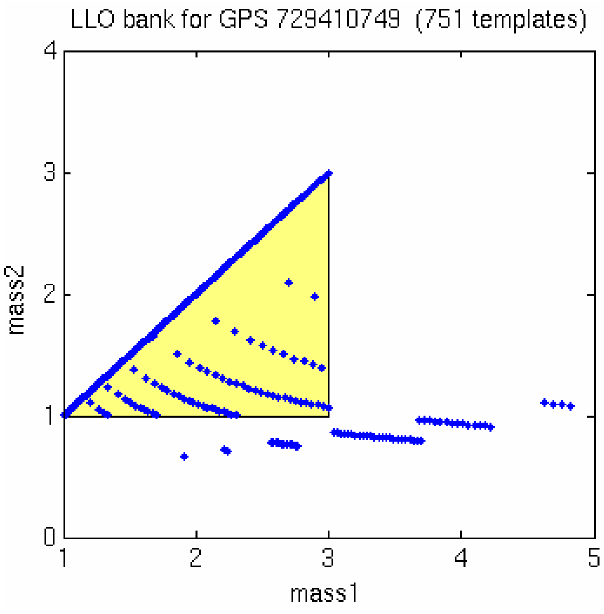
- Triggers separated afterward; only non-playground data used for final result

Template Bank Generation

Template bank generated for each chunk of L1 data

- Use noise power spectrum estimated from that chunk
- Low-frequency cutoff for search: 100 Hz
- Banks with fewest and most templates:





Same template bank used for all three interferometers

- L1 bank used because it is most sensitive

Chi-Squared Test

Tuned using playground data with and without simulated signals

- Chose p=15 frequency bands

Allow large signals to have higher χ^2 values, due to mismatch with discrete template bank

- Keep cut rather loose, to avoid losing real signals

L1: $\chi^2 \le 5\left(p + 0.01\,\rho^2\right)$

H1, H2: $\chi^2 \le 12.5\left(p + 0.01\,\rho^2\right)$

(Plots of ρ vs. χ^2, for data and simulated signals, should go here)

Auxiliary-Channel Vetoes

There are occasional "glitches" in the gravitational-wave channel

- Transients larger than would be expected from Gaussian stationary noise
- Chi-squared test eliminates many, but not all

Checked for corresponding glitches in other channels

- Environmental channels (accelerometers, etc.)
- Auxiliary interferometer channels

Found a fairly effective veto for L1

- "L1:LSC-POB_I" with a 70 Hz high-pass filter
- Eliminates 13% of inspiral triggers with SNR>8 (and more at higher SNR)
- Deadtime = 3.0%
- Used hardware injections to verify that a gravitational wave would not appear in this channel

No effective veto found for H1 or H2

Coincidence Requirements

An "event candidate" is required to be detected by same template in L1 and in either H1 or H2

If all three operating, then must be detected in all three
unless too weak to be detected in H2

If on the edge of detectability in H2, it is searched for but not required

Consistency criteria depend on the detector pair

	L1-H1 / L1-H2	**H1-H2**
Time:	Δt < 11 ms	Δt < 1 ms
Effective distance:	No requirement, since LHO and LLO are not exactly co-aligned	$\frac{\lvert D_{\mathrm{H1}} - D_{\mathrm{H2}} \rvert}{D_{\mathrm{H1}}} < 0.5 + \frac{2}{\rho_{\mathrm{H1}}}$

Analysis Pipeline

Have developed automated "pipeline" to filter appropriate data chunks and check for coincidences

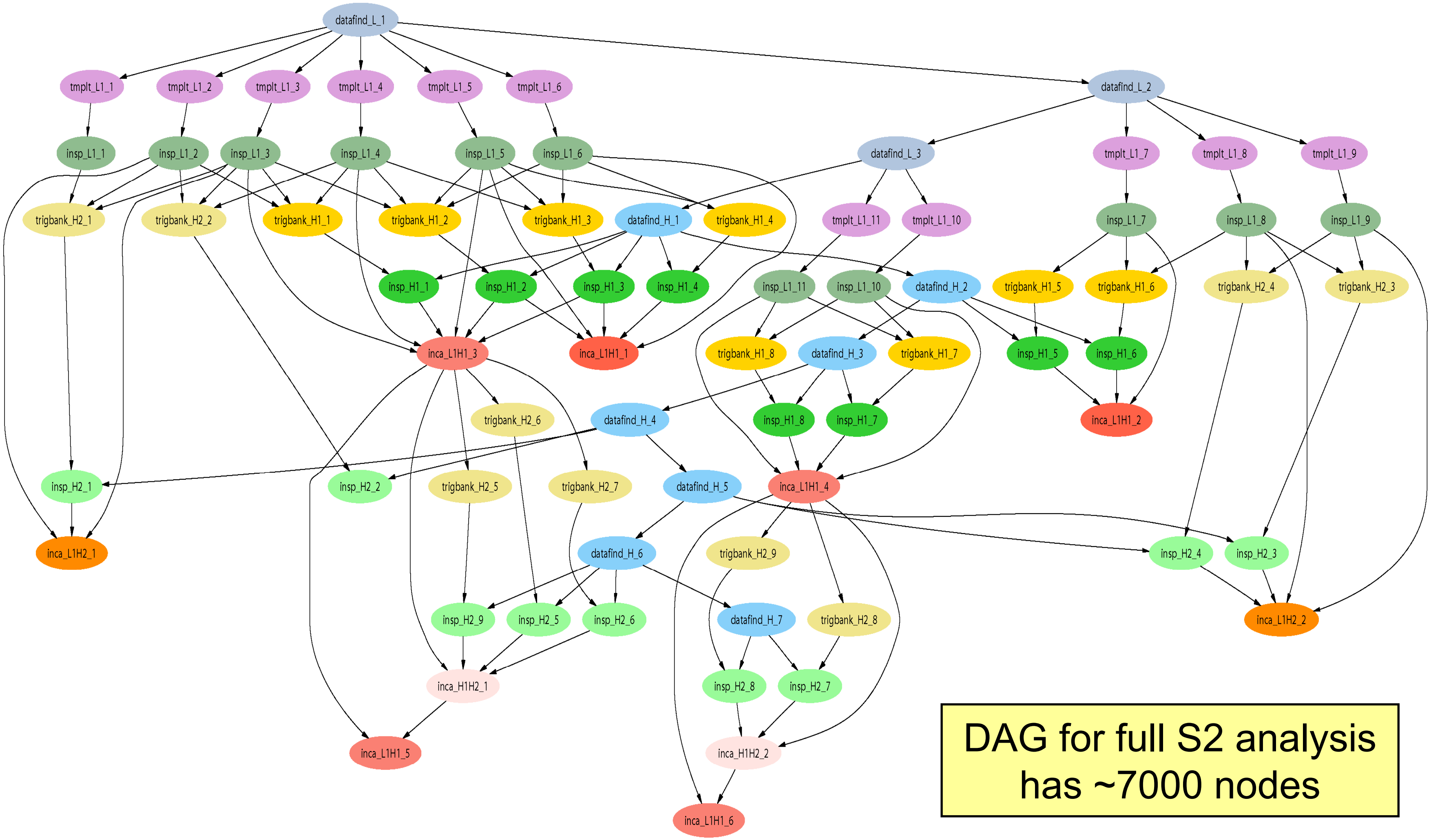
- Dependencies of processing steps expressed as a Directed Acyclic Graph (DAG) generated from a parameter file
- Analysis runs on a Condor cluster using DAGMan meta-scheduler

Pipeline is designed to avoid unnecessary processing

- Only process chunks which belong to "L1 and (H1 or H2)" data set
- For each L1 chunk, generate template bank
- Filter L1 data to produce triggers
- Filter H1 / H2 chunks using **only** those templates which yielded at least one L1 trigger in the corresponding L1 chunk
- Check for coincident triggers
- In 3-interferometer data, filter H2 using templates which yielded L1-H1 coinc

Final output from pipeline is a list of event candidates

Sample Inspiral DAG



DAG for full S2 analysis has ~7000 nodes

Background Estimation

Filtering used a low SNR threshold = 6

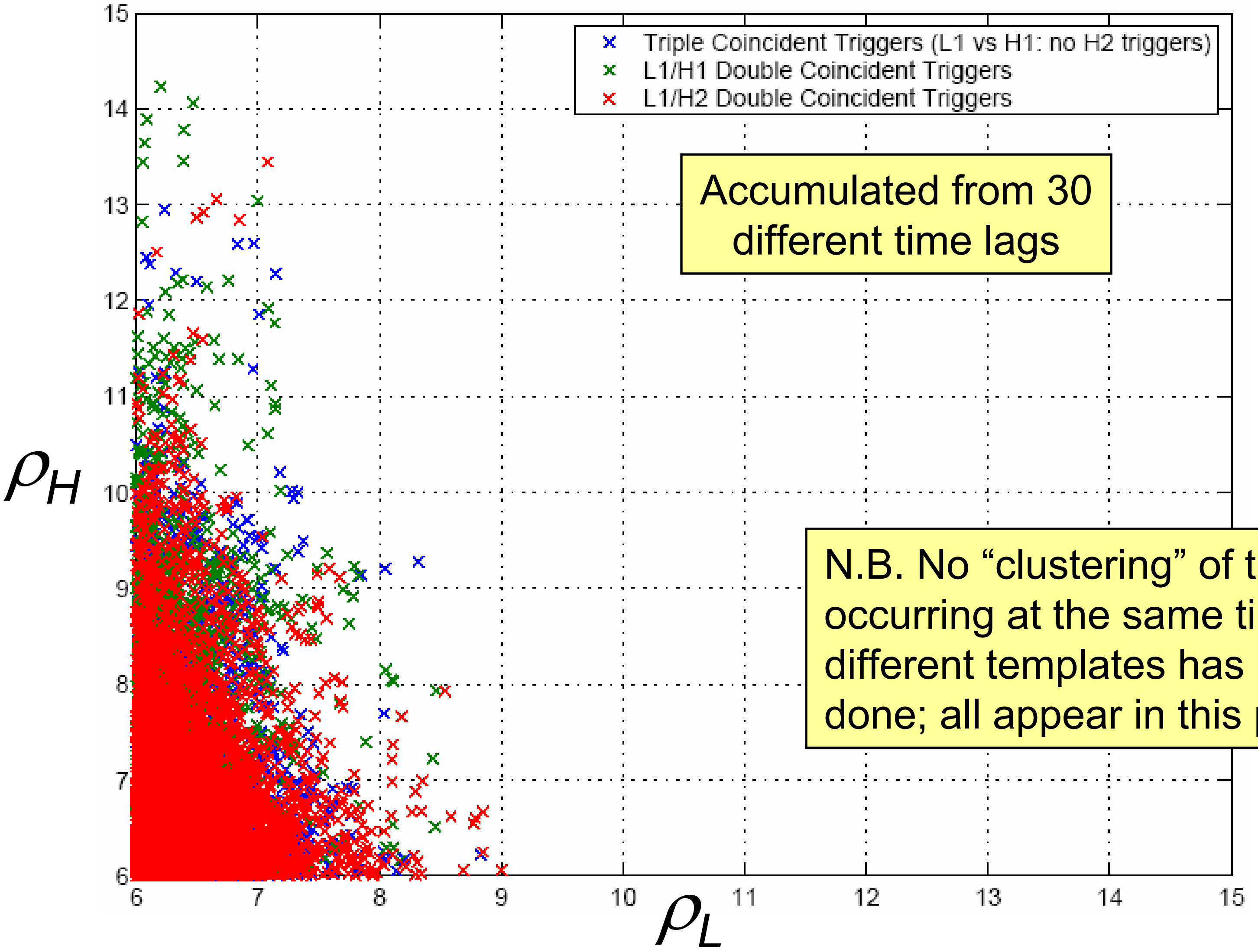
- Many triggers are found in each interferometer with SNR ≈ 6 – 8
- ➔ Expect some accidental coincidences

Estimate background by time-sliding triggers

- Introduce artificial lag in H1/H2 trigger times relative to L1
  - Keep H1 and H2 together, in case of any local correlations
- Use many different lags (+ or –) between 17 sec and a few minutes
- Collect event candidates passing analysis pipeline
  - Only have to re-do coincidence tests, not matched filtering
    (DAG was generated to support time lags of up to several minutes)

Did this before looking at true (un-slid) coincidences

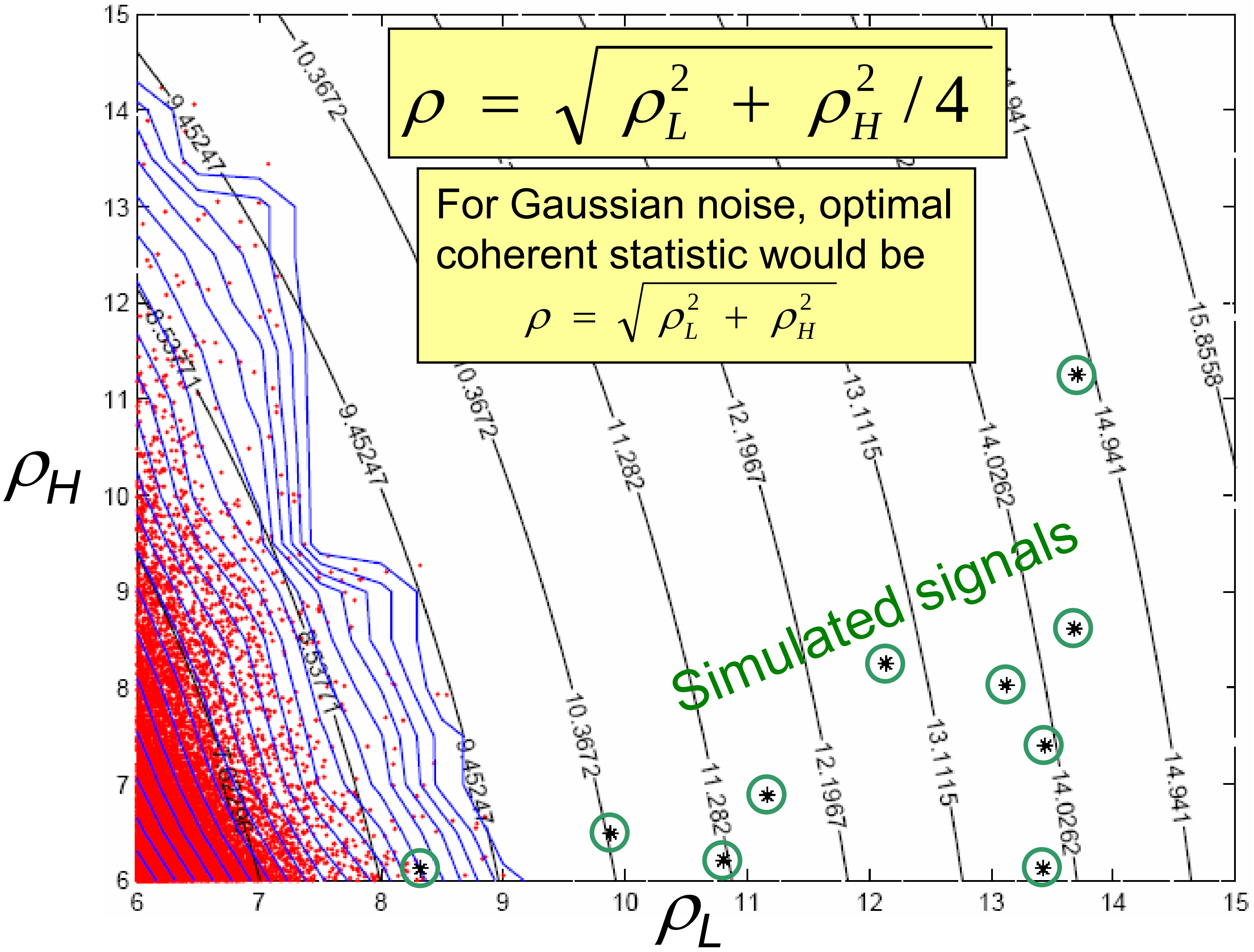
Background Event Candidates



Accumulated from 30 different time lags

N.B. No “clustering” of triggers occurring at the same time in different templates has been done; all appear in this plot

Empirical Figure-of-Merit Statistic

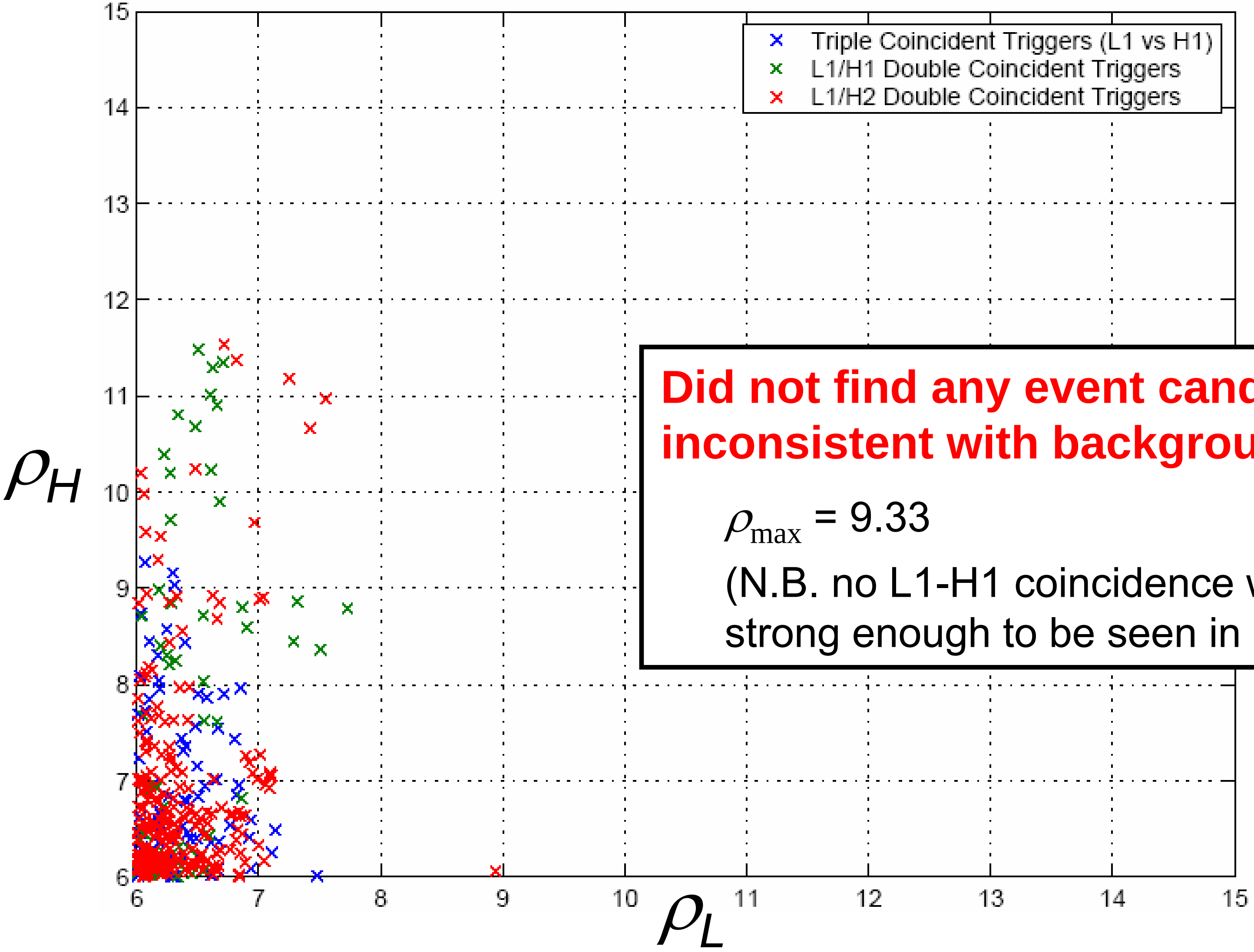


$$\rho = \sqrt{\rho_L^2 + \rho_H^2 / 4}$$

For Gaussian noise, optimal coherent statistic would be

$$\rho = \sqrt{\rho_L^2 + \rho_H^2}$$

Event Candidates Observed



Did not find any event candidate inconsistent with background

$\rho_{\max}$ = 9.33

(N.B. no L1-H1 coincidence was strong enough to be seen in H2)

Upper Limit Calculation

Base calculation on the observed $\rho_{\mathbf{max}}$

No event candidates (real or background) were observed with $\rho > 9.33$ in $T_{\mathrm{obs}} = 354$ hours of data

Efficiency of analysis pipeline, given this $\rho_{\mathbf{max}}$

Fraction of target population sources which would be found with $\rho > 9.33$:

$\varepsilon = 20.0 \pm 0.5\ \%$ ($N_{\mathrm{MWEG}} = 5.3$ in target population)

Take expected background into account

Chance of all background events having r < 9.33 :

$P_b = 0.8 \pm 0.1$

Frequentist confidence interval construction

$$R_{90\%} = \frac{2.303 + \ln P_b}{\varepsilon\, T_{\mathrm{obs}}\ N_{\mathrm{MWEG}}}$$ = 50 per year per MWEG *(preliminary)*

Other Binary Neutron Star Searches in Progress

Joint analysis of LIGO S2 + TAMA DT8

- Will use rest of LIGO S2 data (~700 hours) requiring coincidence with TAMA
- Will exchange trigger data, look for coincident triggers

Search using LIGO+GEO S3 data

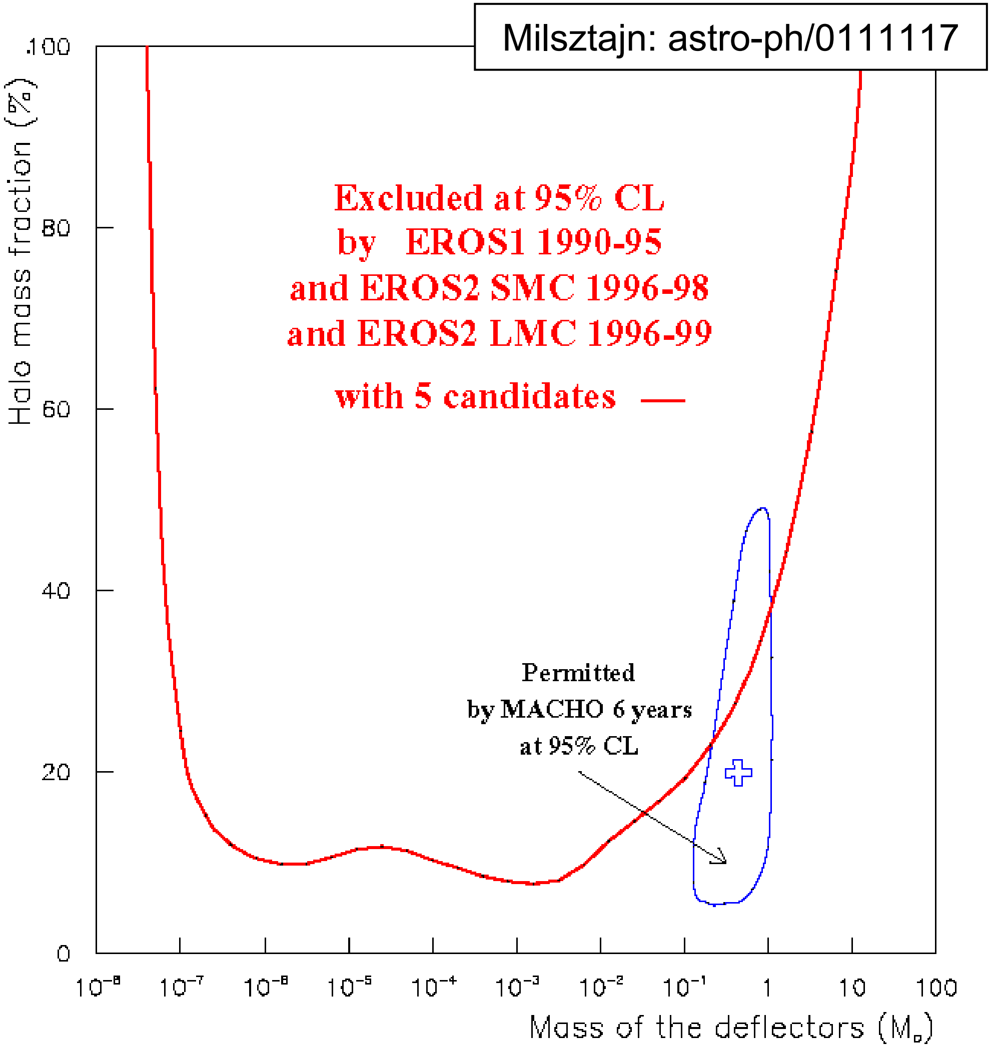
Max. visible range:
(for 1.4+1.4 $M_\odot$,
optimally oriented,
SNR=8)

H1: **~4 to 10 Mpc**
L1: ~2.5 Mpc
H2: ~2 Mpc
GEO: ~45 kpc (operated for part of S3 run)

- All 3 LIGO interferometers sensitive to the Local Group
- Three-site coherent analysis is interesting but challenging

Binary Black Hole MACHO Search

- **Galactic halo mass could consist of primordial black holes with masses $\lesssim 1\, M_\odot$**
  - Some would be binaries inspiraling within the age of the universe
- **Simple extension of binary neutron star search**
  - S2 data being analyzed now
- **Mass range limited by available CPU**
  - Probably can go down to $m = (0.25\sim 0.3)\, M_\odot$ easily


Milsztajn: astro-ph/0111117

Search in Progress for Non-Spinning Binary Black Hole Systems

Waveforms not known reliably

- Target masses: 3+3 to 20+20 $M_\odot$
- Post-Newtonian expansion breaks down while in LIGO frequency band

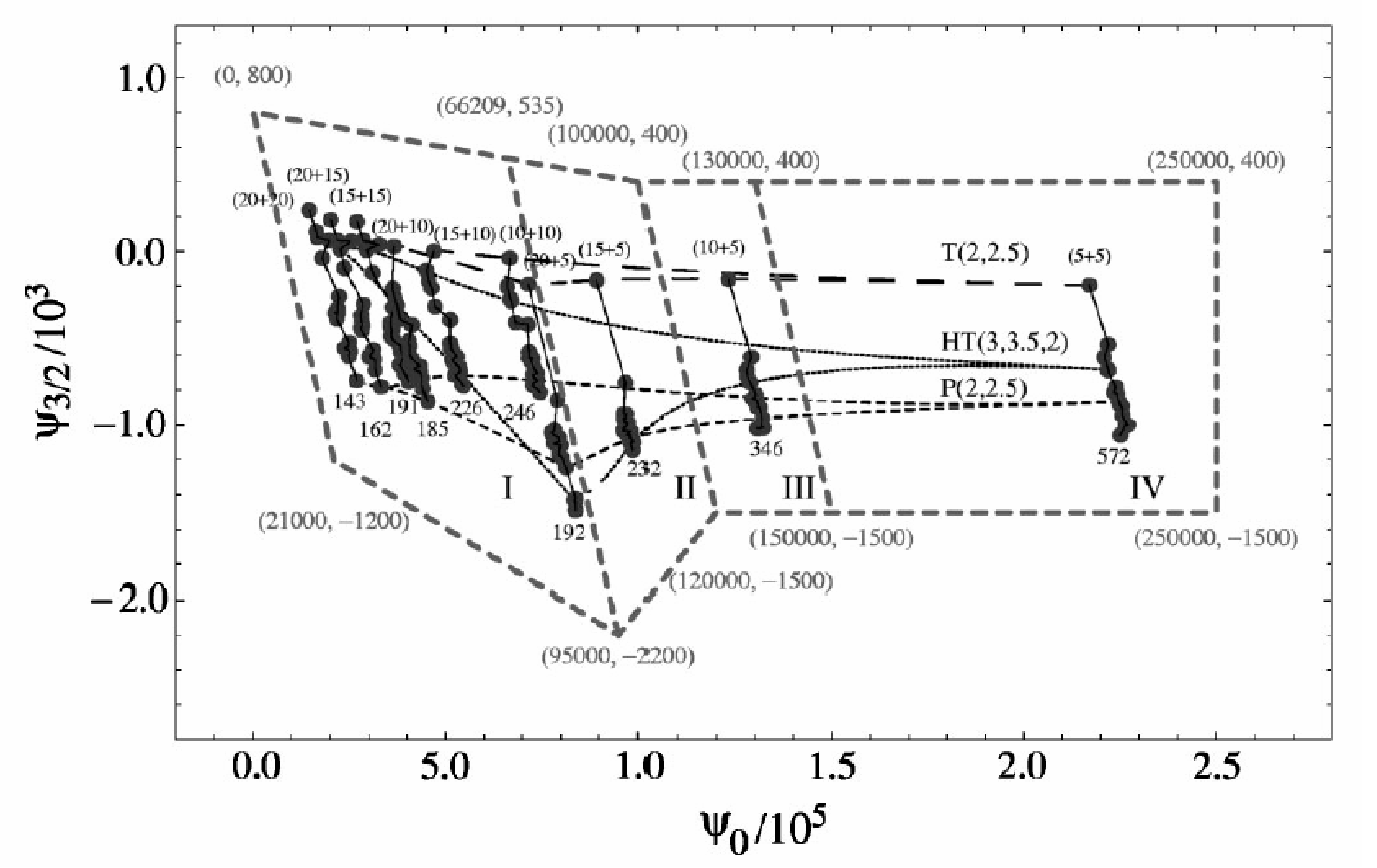
Use matched filtering with "BCV detection template family"

- Buonanno, Chen, and Vallisneri, Phys. Rev. D **67**, 024016 (2003)
- Semi-empirical template waveforms, like post-Newtonian but with additional parameters
- Can achieve good matching to various model waveforms
  - Adiabatic, non-adiabatic, stationary phase, effective-one-body, …
  - Taylor vs. Padé expansions

Algorithm implemented; studies in progress

- Template bank generation
- Parameter ranges corresponding to physical signals
- Issue: how to perform a χ^2 test for very short signals

BCV Parameter Space (Projected)



Plan to Search for *Spinning* Binary Black Hole Systems

Spin complicates waveforms considerably

- Precession ➔ phase and amplitude modulation
- Introduces several additional signal parameters

BCV have treated this in the adiabatic-inspiral limit

- Phys. Rev. D **67**, 104025 (2003)
- Continue “detection template family” approach
- Introduce sinusoidal phase modulation
- Leads to a manageable parameter space

Also shown to be good for black hole–neutron star systems

Summary

Binary neutron star inspiral rate limit published using S1 data

Searched for binary neutron star inspirals in LIGO S2 data

- Analysis pipeline designed for coincident detection
- No coincident event candidates observed above background
- *Preliminary* upper limit: Rate < 50 per year per MWEG

Currently doing several analyses using S2 and S3 data

- Combined analysis with other interferometer projects
- Lower- and higher-mass systems

Interferometers are getting sensitive enough to see binary systems out into the universe !